CHAPTER 2

Literature Review

2.1 Outline

The turbulent wall jet is seen in many engineering equipment and scientific research applications. The various applications (discussed in chapter 1) of the turbulent wall jet attracted many authors to study physics and different mean and turbulent flow characteristics. Glauert [49] was the first author, who investigated the wall jet. The author suggested that wall jet can be analysed into two different layers noted as boundary layer and free layer. Further, this theory was analyzed by many authors through experimental and numerical methods. Launder and Rodi [50, 51] summarized the turbulent wall jet studies for two and three-dimensional wall jet and noted that the flow field of the wall jet comprises into two different shear layers called as the upper and lower shear layers. The upper shear layer behaves like a free jet whereas lower shear layer interacts with the bottom wall. The lower shear layer develops at the wall and forms a boundary layer region. Further, authors have categorized the flow development into three different regions (Figure 2.1). The first region ($0 \leq x/d \leq 4-5$), where the velocity and temperature remain constant and equal to the jet inlet condition, is known as the potential core region. The second region ($4-5 \leq x/d \leq 20$) is the transition region, where the entrainment of the ambient fluid occurs at a high rate and decay of the mean velocity and thermal energy diffusion are very rapid. The third region ($x/d \geq 20$) is the developed region, where the mean velocity and temperature profile show the self-similar behavior. These kind of the wall jets are strongly influenced by the initial (like: top hat, fully developed, developing, Reynolds number, tur-

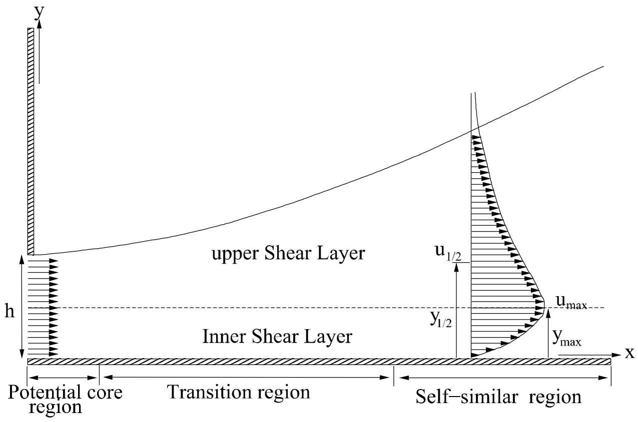


Figure 2.1: Characterization of the flow domain of a plane wall jet

bulence intensity) and boundary conditions (like: sinusoidal wavy surface, surface roughness and enclosure width).

This chapter summarizes the previous studies of the turbulent jets for different initial and boundary conditions. The literature related to initial conditions are first presented for turbulent jets. Then, the turbulent jets are reviewed for different boundary conditions for heat transfer and fluid flow characteristics. The noted literature related to these studies are presented in the subsequent sections.

2.1.1 Literature related to different initial conditions

In this section of the literature review, effect of the different initial conditions on the mean and turbulent flow flow-field of the turbulent jets are presented. A detailed summary of the different initial conditions are listed in table 2.1.

The initial conditions of the jet are studied in free and wall jet by varying the nozzle exit velocity profiles, nozzle geometry, Reynolds numbers and turbulence intensity. Bradshaw [59] was the first author, who investigated the effect of initial conditions for a plane wall jet. The author noted that the mixing layer of the jet becomes fully developed at a distance of thousand times of the initial momentum thickness, whether the initial conditions are turbulent or laminar. Afterwards, several studies are reported on the effect of initial conditions in different turbulent jets. The description of different initial conditions of the different turbulent jets are presented here followed by its mean flow and turbulent characteristics. The velocity profiles at the nozzle exit are varied by using the different lengths of the nozzle. The top hat velocity profile is obtained with the contoured nozzle. The sufficiently long nozzle or channel generates the fully developed velocity profile at the nozzle exit. The jet characteristics generated by different jet exit velocity profiles are

Authors	Re	Jet exit velocity profile	Regions	Spread rate $\frac{dy_{1/2}}{dx}$	Spread rate $\frac{dz_{1/2}}{dx}$	n
Free jet						
Hussain and Clark [52]	32,550 81,400	top hat and fully developed	$0 \le x/d \le 40$	-	-	1
Obot et al. [53]	13,000 22,000	Developing $l/d = 1$ Developing $l/d = 12$	$0 \le x/d \le 25$	0.088 0.078	0.088 0.078	-
Ferdman et al. [54]	24,000	Fully developed axisymmetric & asymmetric	$0 \le x/d \le 80$	0.090	0.088	-
Xu and Antonia [20, 55]	86,000	top hat and fully developed	$0 \le x/d \le 80$	-	-	-
Wall jet						
Newman et al.[56]	16,400	fully developed	$20 \le x/d \le 200$	0.053	0.52	1
Davis and Winrato [57]	170,000	top hat	$0 \le x/d \le 65$	0.037	0.32	1.15
Rajaratnam and Pani [1]	59,500-97,500	top hat	$3 \le x/h \le 70$	$0.040 - 0.045$	$0.20 - 0.27$	1
Padmanabham and Gowda [2]	95,400	fully developed	$0 \le x/d \le 100$	$0.040 - 0.045$	$0.216 - 0.250$	1.15
Sun and Ewing [4]	65,000–108,000	fully developed top hat	$0 \le x/d \le 90$	0.053 0.060	0.27 0.28	1.14 1.19
Maslov et al. [58]	25,000-125,000	top hat	$50 \le x/d \le 350$	0.056 ± 0.001	0.30 ± 0.01	-
Hall and Ewing [9]	89,600	fully developed	$3 \le x/d \le 60$	0.051	0.28	1.144
Agelin-Chaab and Tachie [11]	5,000 10,000 20,000	fully developed	$0 \le x/d \le 120$	0.054	0.255	1.15

Table 2.1: Summary of the free and wall jet for different initial conditions

studied in free jets [20, 52, 54, 55, 60] and wall jets [2, 4, 9, 11, 56]. The jet initial velocity profiles strongly influence the mean and turbulent flow characteristics inside the flow domain. There are a number of authors who studied the flow characteristics for the different shapes of the nozzle geometry [1, 2, 28, 29, 61]. Liu et al. [62] studied the effect of nozzle contraction ratio (CR), which is varied from 1 to 4. The initial condition of the jets is also varied by changing the jet exit Reynolds number [4, 11, 63–67] and turbulence intensity. The effect of Reynolds number is seen in near field. The far-field of the similarity region becomes independent of the Reynolds number. Some of the investigations for different wall and jet combinations at different jet initial conditions are also reviewed in this section for the different jet characteristics.

Hussain and Clark [52] have investigated the effect of top hat and fully developed velocity profiles for a plane jet at the Reynolds number of 32,550 and 81,400. The initial conditions of the jet strongly influence the mean and turbulent flow characteristics. The decay rate for the centerline mean velocity is higher for turbulent condition than the laminar condition. The spread rate for the turbulent condition is lower than the laminar condition. This is due to the development of the small scale dissipative turbulence rather than the lateral diffusion of the streamwise momentum. Obot et al. [53] studied the effect of nozzle length on the large scale properties (like mean velocity decay, turbulent intensity, spread rates) for a round jet at the Reynolds number of 13,000 and 22,000. They have used a single round jet with two combinations of length to diameter (l/d) ratio, i.e. 1 and 12. They concluded that $l/d = 1$ nozzle showed higher decay and spread rate than $l/d = 12$ nozzle. Also, the nozzle $l/d = 1$ showed higher entrainment than the nozzle $l/d = 12$ in near field. Ferdman et al. [54] compared the two nonuniform initial velocity profiles (axisymmetric fully developed and asymmetric) for a round free jet with the top hat velocity profile at a Reynolds number of 24,000. The axisymmetric fully developed velocity profile generated by a long circular straight pipe. The asymmetric velocity profile generated by bending the nozzle 90^0 before exit. The two jet inlet profiles (axisymmetric fully developed and asymmetric) have a lower initial growth of the turbulence intensity and a lower far-field decay rate than the top hat profiles. Further, there are many researchers [20, 55, 60] who investigated the different characteristics of the top hat and fully developed velocity profiles generated in free jet. They observed that in smooth contoured nozzle, the jet develops more rapidly than in the long pipe. The far field decay rate in the long pipe is smaller than the decay in the smooth contoured nozzle. Further, in continuation of the effect of initial condition on flow field, Liu et al. [62] studied the effect of nozzle contraction ratio (CR) of the two parallel nozzles. The authors varied the contraction ratio of the nozzle from 1 to 4 and found that sudden contraction of the jet significantly enhances the mixing between the parallel jets. The sudden contraction of the jet enhances the turbulence inside the flow domain and the jet spreads faster than the lower contraction ratio of the jet. Bogey and Bailly [63] studied the effect of Reynolds number for a round jet through large eddies simulation (LES). They varied the Reynolds numbers between 1,700 and 4,00,000 and reported that the jet development is slower in the near field region with decrease in the Reynolds number. In the near field, the decay rate of the jet centerline mean velocity increases with increase in the Reynolds number. Suresh et al. [64] also studied the effect of Reynolds number for a rectangular nozzle with an aspect ratio of 20. They concluded that the large scale properties show the strong dependency on the Reynolds number while it becomes independent in far-field at the high Reynolds numbers. Fellouah et al. [65] studied the effect of Reynolds number for a round jet with a hot wire anemometer. They found that the streamwise mean velocity profile is independent of the Reynolds number in the near field region. An experimental study using hot wire anemometer is conducted by Xu et al. [66, 67] while considering five different Reynolds numbers. It has been observed that the large scale properties and small scale properties are dependent on the Reynolds number up to 30,000; after 30,000, it becomes almost independent in far field region.

Newman et al. [56] investigated the three-dimensional wall jet at a Reynolds number of 16,400 for a fully developed jet exit velocity profile. The authors measured the mean velocity and turbulence intensity profiles in the range of $20 \leq x/d \leq 200$. The decay rate of the mean velocity along the downstream direction is 1. Newman et al. [56] reported that the wall-normal growth rate is approximately seven times lower than the lateral growth rate of the flow stream. The non-dimensional longitudinal turbulence intensity in three-dimensional wall jet is measured approximately 50% higher than the two-dimensional wall jet. Davis and Winrato [57] studied for the three-dimensional wall jet for top hat profiles generated by contoured nozzle at the Reynolds number of 170,000. Davis and Winrato [57] noted the constant spread rate in lateral and wall normal directions after the downstream location $x/h > 40$. The spread rate in lateral and wall-normal directions are 0.32 and 0.037, respectively. Maslov et al. [58] also studied the effect of top hat profile at the Reynolds numbers 25000-125000. Rajaratnam and Pani [1] extensively investigated the influence of circular, elliptic, square, rectangular, and equilateral triangular shapes of the orifice (Figure 2.2) on the flow field of the three-dimensional turbulent wall jet. They have noted that the decay of local streamwise velocity is independent of the initial conditions of the nozzle in the region of $x/\sqrt{A} \geq 60$, where A is the cross-sectional area of the nozzle. The authors have reported that the wall-normal spread is approximately independent on the nozzle shape in the region of $x/d > 40$ or $x/h > 40$. The nozzle shape influenced the lateral spread, and it is approximately 30% higher for the square orifice nozzle than the

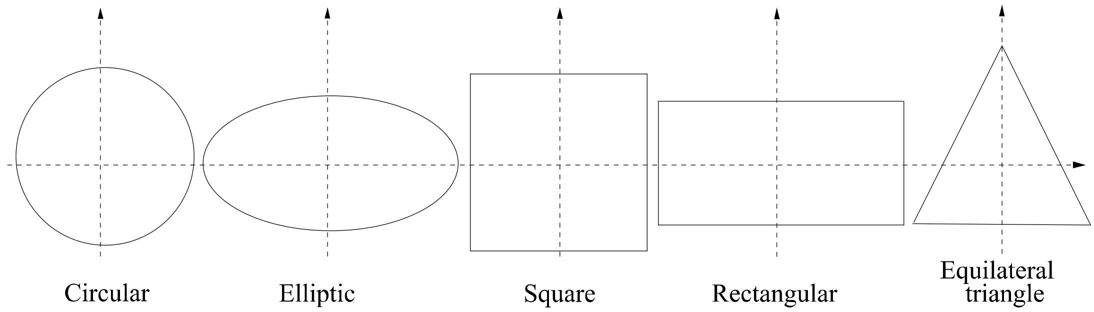


Figure 2.2: circular, elliptic, square, rectangular, and equilateral triangular orifices to generate the three-dimensional wall jet investigated by Rajaratnam and Pani [1]

circular orifice nozzle. Padmanabham and Gowda [2, 3] studied the effect of the different nozzle geometries on the mean flow and turbulence characteristics. They considered various segments (h/d = 1.0, 0.8, 0.5 and 0.23) of the circular orifice at the nozzle exit as shown in Figure 2.3. The decay rate of the local maximum velocity followed the power law function and it is found independent of the nozzle geometry. The orifice geometry significantly affected the wall-normal and lateral spread rates. It is observed that the lateral spread rate increases with decrease in the orifice segment height (h). The spread rate in the circular segment orifice is approximately 8% and 12% higher than the circular orifice nozzle in the lateral and wall-normal directions, respectively. Padmanabham and Gowda [2] also examined the Reynolds shear stress for the nozzle segment $h/d = 0.8$ at the different downstream locations. The root mean square (rms) of the streamwise velocity fluctuations u' are measured along the longitudinal direction at the jet centerline and in lateral direction at the y_{max} plane. The u' profile almost collapsed after the downstream location $x/h = 50$. The location of the zero shear stress shifted towards the wall from the location of the maximum velocity due to the presence of higher turbulence in the outer shear layers. Abrahamsson et al. [12] reported that the lateral and wall-normal spreads of the contoured nozzle are 15% and 20% higher than the long pipe nozzle. Sun and Ewing [4] studied the three-dimensional wall jet by varying the initial velocity profiles. The authors have considered the top hat and fully developed velocity profiles generated by a contoured nozzle (the contour on inside nozzle is of fifth order polynomial with area contraction ratio of 28:1) and a long pipe ($l/d = 60$). The generated velocity profile at the nozzle exit is shown in Figure 2.4. They noted that the mean flow and turbulent characteristics are independent of the initial conditions in the intermediate region. The authors also studied the effect of Reynolds number (ranging from 65,000 to 108,000) on the spreading behaviour of the three-dimensional wall jet, and reported that the spread of the three-dimensional

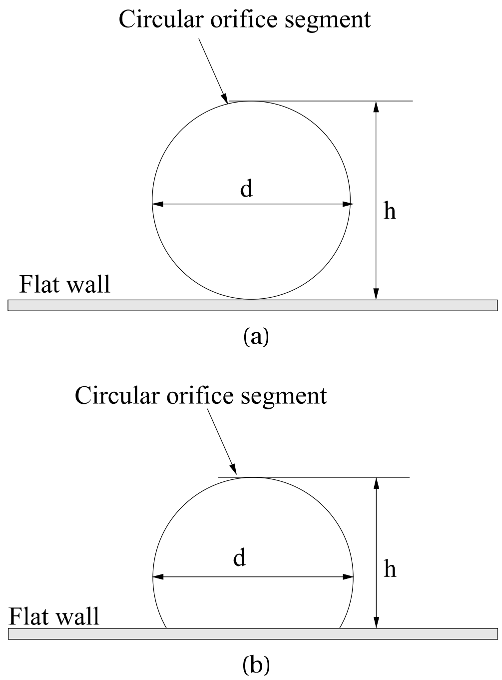


Figure 2.3: Schematic of circular orifices segment to generate the three-dimensional wall jet investigated by Padmanabham and Gowda [2, 3]

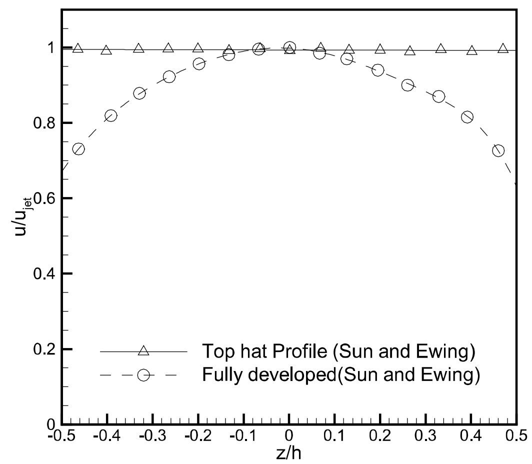


Figure 2.4: Initial velocity profile at nozzle exit investigated by Sun and Ewing [4]

wall jet is approximately independent of the Reynolds number. Sun and Ewing [4] also reported the normal stresses at the downstream locations $x/h = 20$, 30 and 40. The normal stresses in the two jets are found almost similar to each other with the normalised scales as u'/u_{max} vs $y/y_{1/2}$ or $z/z_{1/2}$. Hall and Ewing [9] investigated the effect of the nozzle aspect ratio (nozzle-width (W)/nozzle-height(h)) in a three-dimensional wall jet generated by a rectangular nozzle. The nozzle aspect ratio was varied from 1 to 8 at the Reynolds number of 89,600 for the fully developed jet exit velocity profile. The velocity decay rate collapsed on a single curve when the downstream locations of the jet is normalised by the square root of the jet exit cross-section. The authors presented the spread width of the jet with a modified normalised scale in the wall-normal ($(y_{1/2}-h)/\sqrt{A}$) and lateral ($(z_{1/2}-W)/\sqrt{A}$) directions along the downstream locations ($x/\sqrt{A}$) and found that the spread rate is independent of the nozzle aspect ratio. The spread rate of the flow stream in the lateral direction was approximately 5.5 times more than in the wall-normal direction. The spread and decay rates are shown in table 2.1. Agelin-Chaab and Tachie [11] studied the effect of Reynolds number on a three-dimensional circular wall jet for a fully developed jet exit velocity profile. The Reynolds numbers (Re) were taken as 5,000, 10,000 and 20,000 based on the jet exit velocity and nozzle diameter. Insignificant effect of the Reynolds number on the decay and spread rates in self-similar region was noted. The turbulent intensity profiles, after the downstream location $x/h > 40$, collapsed with each other. The Reynolds shear stress $< u'v' >$ showed antisymmetric distribution in inner and outer shear layers. The inner shear layer showed the negative shear stress $< u'v' >$ whereas outer shear stress showed the positive value. The difference in wall-normal position of zero shear stress and the mean shear gradient is an intriguing characteristic coming from this distribution. The effect of three different nozzle geometries have been studied by Rahman et al. [5]. They considered the nozzle geometries like circular, square and rectangular with same exit area to characterise the turbulent characteristics and flow structure of the turbulent jets. They reported that the mixing and entrainment are highest in the near field for the rectangular nozzle as compared to the circular and square ones. The authors observed that the non-circular nozzle shows a lower potential core length (approximately 33%) than the circular nozzle. Godi et al. [28] studied the influence of nozzle geometry on the flow and heat transfer characteristics of a three-dimensional turbulent wall jet. The local and spanwise average Nussult numbers were strongly influenced by the nozzle exit diameter. They further concluded that the square jet is advantageous over the circular jet for different jet characteristics.

Some of the investigations on different wall and jet combinations for different jet initial conditions are also reviewed, which are as follows:

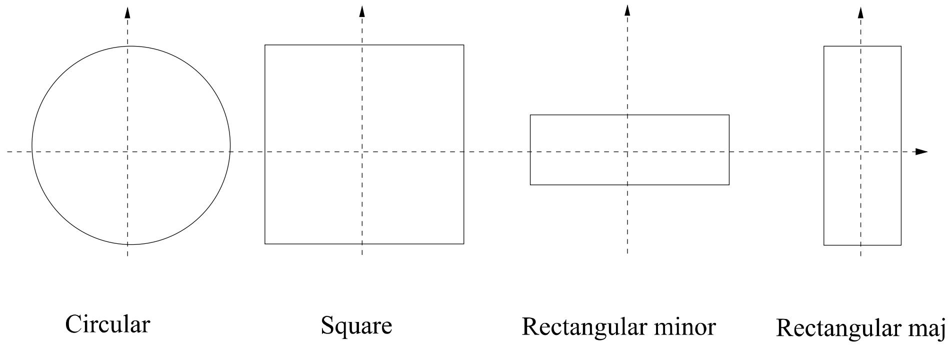


Figure 2.5: Schematic diagram of nozzle geometries investigated by Rahman et al. [5]

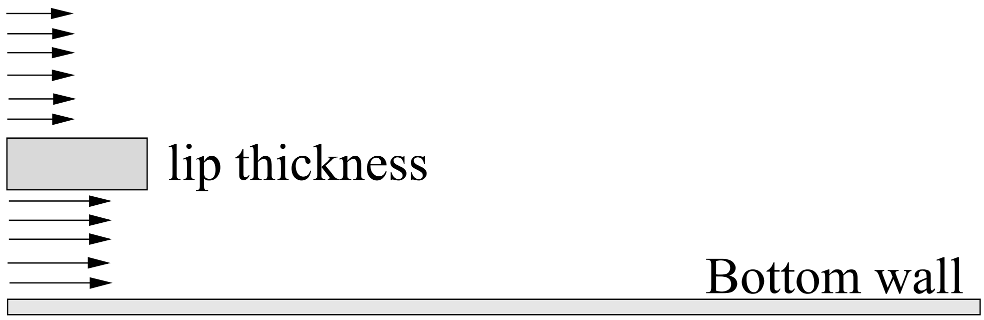


Figure 2.6: Schematic diagram of nozzle lip thickness investigated by Mclntyre et al. [6]

Assoudi et al. [68] made a comparison between an offset jet and a dual jet (a combination of a wall jet and an offset jet) for different offset ratios, jet exit velocity and jet exit temperature. They reported that the development of the flow strongly depends on the offset ratio. Mclntyre et al. [6] studied the effect of the top nozzle lip thickness (Figure 2.6) on a wall jet at the Reynolds number of 30,700 in a co-flowing jet condition. They reported that the effect of the nozzle lip thickness becomes insignificant on the spreading of the wall jet. Dong et al. [69] studied the effect of incidence angle on the heat transfer characteristics for the impinging jet. They noticed that the maximum heat flux point shifts away from the geometrical impingement location by reducing the angle of incidence. Further, the effect of diameter ratio of the annular nozzle, distance between the nozzle plane and the impingement surface have been studied by Ichimiya [70]. The author also examined the effect of Reynolds number on the radial distribution of the local Nusselt number. A numerical study of a two-dimensional wall jet for different initial conditions has been carried out by Kechiche et al. [71]. They considered low Reynolds number turbulence model proposed by Herrero et al. [72] for the numerical simulation, and reported the different jet characteristics. They used the modified value of the empirical constant $C\mu$ in the Kolmogorov–Prandtl eddy viscosity relation as suggested by Ljuboja and Rodi [73], instead of 0.09. By using the low Reynolds number $k-\epsilon$ turbulence model, Mohammadaliha et al.

[29] studied the effect of nozzle geometry for a three-dimensional offset jet and compared the flow field created by the two different shapes of the nozzle profile, i.e. circular and square. They reported that the square shape of the nozzle has higher mixing rate, spread rate and flow entrainment as compared to the circular nozzle.

2.1.2 Literature related to different boundary conditions

In this section of the literature review, the heat transfer and fluid flow characteristics for the different boundary conditions of the turbulent jet are presented. The boundary conditions of the jet are varied by changing the geometrical configurations of the flow domain (back wall, sidewall, wavy wall surface, step wall). The effect of the different boundary conditions on the turbulent flow stream is studied for the heated jet and unheated jet. The study of heated jet provides the turbulent diffusion by using the heat as the passive scalar. The turbulent diffusion of the heated jet can be used in the study of the other scalar species diffusion such as diluted pollutant [7]. The study of unheated jet provides different fluid flow and turbulent characteristics on account of different boundary conditions. The effect of boundary conditions on the turbulent jet is reviewed in two different groups, i.e. heated jet and unheated jet, which are discussed below.

2.1.2.1 Literature related to heat transfer characteristics

In the last four decades, the heat transfer characteristics in turbulent jets are explored for different thermal and geometrical boundary conditions through experimental and numerical methods. The heat transfer characteristics of the turbulent jets are studied by a number of researchers [7, 17, 27, 33, 74–87] for different geometrical (convex, concave, wavy) and thermal (adiabatic, isothermal, constant heat flux) boundary conditions of the bottom wall. The heat transfer characteristics of the heated jet are mainly studied in free jet [18, 20, 88–93] for different initial conditions, but less attention is given to heated jet for different boundary conditions [7, 77, 78, 80, 84, 94–96]. The effect of different boundary conditions for the three-dimensional heated wall jets is summarised in table 2.2. The heated jet is characterised by the decay of the temperature field along the downstream direction, spread of the temperature field in lateral and wall-normal directions, similarity of the temperature profiles and statistical analysis of the fluctuating temperature. The temperature field is divided into three different regions called as potential core region, transition region and self-similar region as shown in Figure 2.7. For the similar initial condition, the boundary conditions affect the heat transfer characteristics from the jet exit ($x/h \geq 0$). The temperature field near the bottom wall, called as inner shear layer, interacts with the

Authors	Geometry			Temp.	Re	Range
	BTW	BW	SW	$(t_{jet} - t_o)$		
Koso and Ohashi [7]	flat	No	No	10.5^0C	66,200	$0 \leq x/d \leq 50$
Dakos et al. [94]	convex	No	No	12^0C	30,000	$42 \leq x/h \leq 93$
Okamoto and Gibson [77]	concave	No	No	12^0C	30,000	$42 \leq x/h \leq 93$
Belilovsky [97]	flat	No	No	30^0C	55,000	$0 \leq x/d_e \leq 22$
Brindon et al. [98]	flat	Yes	No	25^0C	60,000	$0 \leq x/d \leq 25$

Table 2.2: Different boundary conditions on heated three-dimensional wall jet, BTW=bottom wall, BW= back wall, SW=sidewall.

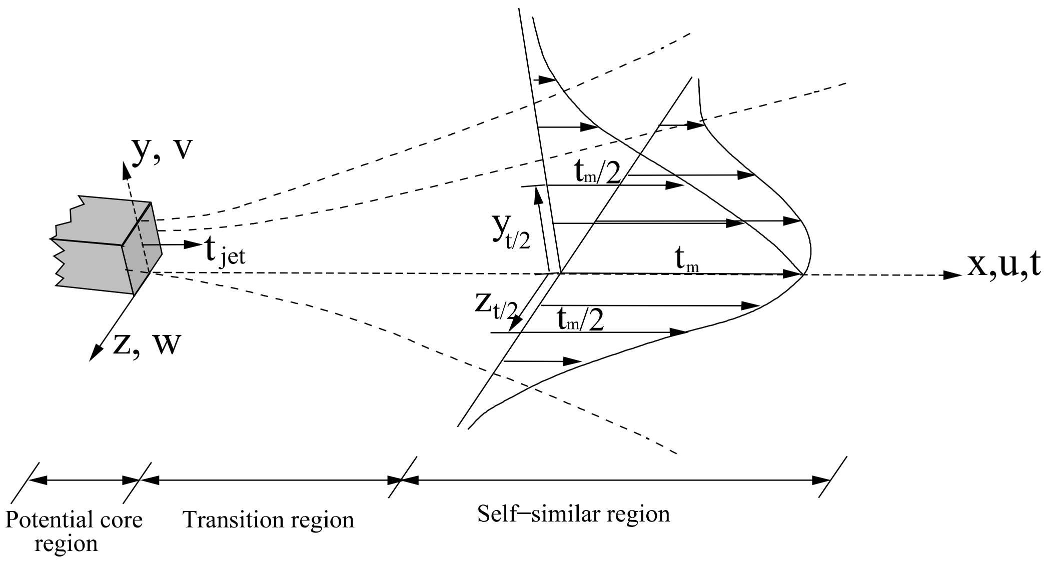


Figure 2.7: Characterisation of the flow domain of a three-dimensional heated wall jet

geometry of the bottom walls, while the outer layer, called as upper shear layer, interacts with the surrounding fluids. Some of the authors also reported the statistical analysis with second and fourth order moment of the heated free jet, and it is seen that the fluctuating temperature follows the normal distribution in self-similar region. In this section, the literature related to the heat transfer characteristics of turbulent wall jet and offset jet are reviewed.

Nizou [74] was the leading author to study the heat transfer characteristics of a plane turbulent wall jet for the Reynolds numbers 9,000 to 60,000. The author presented the mean velocity and temperature field for the constant heat flux condition. AbdulNour et al. [79] did the experimental investigation on a planner wall jet with uniform heat flux and isothermal bottom wall boundary conditions at a Reynolds number of 7,700. The temperature fields are measured with the micro thermocouple and an infrared thermal imaging camera. They studied the thermal behaviour near the wall ($0 < x/h < 13$) for the application in automobile defroster and measured the temperature profiles at different streamwise locations. The calculated local heat transfer coefficient is found insensitive at a larger streamwise location ($x/h > 5$). The minimum local heat transfer coefficient is observed at $x/h = 5$. Naqavi et al. [83] studied the heat transfer of the plane wall jet through numerical method at a Reynolds number of 7,500. Naqavi et al. [83] observed that the growth of the thermal boundary layer is slow up-to the downstream location $x/h < 8$, after this location it increased. In the near field ($x/h < 3$), the presence of roll structure in the outer shear layer caused the mixing of the inner and outer shear layer fluid. The mixing of the shear layers is responsible for the diffusion of thermal energy. Gao et al. [81, 99] experimentally studied the co-flowing wall jet to control the flow and thermal characteristics of a planer offset jet at a Reynolds number of $Re = 42,000$. Authors [81, 99] have compared the mean and fluctuating pressure, skin friction coefficient and heat transfer characteristics for different jet exit mass flux ratio and the momentum flux ratio of the wall and the offset jet. The low momentum of the wall jet, in comparison to the high momentum of the offset jet, reduced the turbulent fluctuation and the heat transfer rate and quickly entrained into the offset jet stream in the near fields. In contrast, when the momentum of wall jet is increased, they noted that the high momentum of the wall jet plays an important role on the re-circulation region where the fluctuation in the pressure and heat transfer rate increased. The flow stream of the wall jet remained attached to the bottom wall till farther downstream locations. Further, Gao et al. [82] varied the Reynolds number from $21,800 - 54,500$ and also varied the offset height between $0.2 - 1$. Godi et al. [84] studied the heat transfer characteristics of a three-dimensional wall jet by transient temperature measuring method for the Reynolds numbers 2,000 and 8,000. Authors have used uniform wall heat flux condition over a flat plate without considering any side or backwall. They applied the three different measurement techniques, namely, thermocouple, liquid crystal thermography and infrared thermography. They found that the infrared thermography is best suited technique for the heat transfer characteristics of the wall jet. The developing region had the higher entrainment from the surrounding, that leads to the increase in the Nusselt number.

The heat transfer characteristics of the heated wall jet is an important aspect of the wall jet applications, but it has got very little attention. There are many characteristics of the heated wall jet that need to be explored at different initial and boundary conditions. Koso and Ohashi [7] studied the thermal characteristics of a three dimensional heated wall jet generated by a $2m$ long semicircular nozzle. A fully developed jet exit velocity profile was considered at a jet exit Reynolds number of 66,200. The jet exit temperature was 10.5^0C above the ambient. The jet was blown over a flat plate without considering

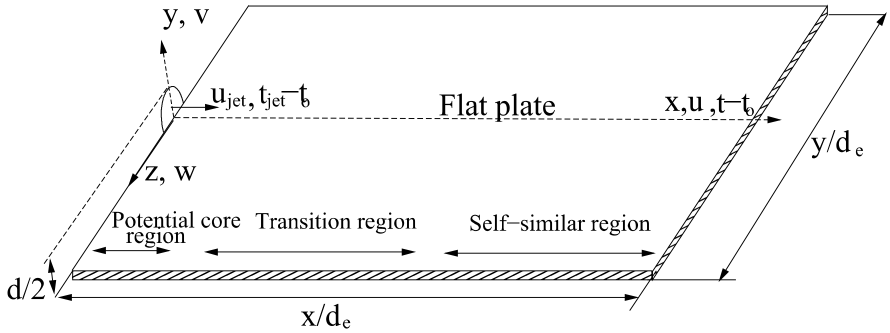


Figure 2.8: Geometrical boundary condition of the three dimensional wall jet investigated by Koso and Ohashi [7]

any side or back wall conditions as shown in Figure 2.8. Koso and Ohashi [7] did not define the thermal boundary condition for the wall jet. The authors have considered the power law function for temperature spreading rate in both the directions. The temperature measurement suggested that the temperature spreading rate in wall-normal direction (1.54 ± 0.18) is less than that in the lateral direction (1.61 ± 0.21). The thermal spreading ratio (lateral to normal thermal spreading rate) was less than the velocity spreading ratio. The temperature in self-similar region ($x/d = 30-45$) decayed as per the power law. The authors have noted the lower temperature decay rate (0.94 ± 0.04) than the velocity decay rate (1.27 ± 0.02). The temperature and velocity gradients strongly influenced the Reynolds stresses ($< u_i' u_j' >$) and the turbulent heat fluxes ($< t' u_i' >$). Craft [78] studied the three-dimensional heated turbulent wall jet at a Reynolds number of 3,500 through numerical technique. A back wall at the jet exit plane is considered. Also, smooth flat plate condition of the bottom wall was considered. Author used the low Reynolds number second moment closure model method to predict the velocity and temperature fields. Similar to Koso and Ohashi [7], Craft [78] also noticed the lower spread rate for the thermal field than the velocity field. The spread rate of the temperature field is observed to be 0.07 and 0.518 in the lateral and wall-normal directions, respectively. Dakos et al. [94] investigated the fluid flow and thermal behaviour of a heated plane and curved wall jet at a Reynolds number of 30,000. The co-flow condition ($u_1/u_{jet} = 0.57$) was applied at the inlet of the heated wall jet. The mean temperature was measured with the 12 μm diameter of the chromel-alumel thermocouple probe coupled to a standard miniature hotwire anemometer. In the curved wall jet, a little decrease in the skin friction coefficient was noted and a significant increase in the Stanton number was observed as compared to the plane wall jet. They also marked that over 90% of the temperature change from the wall is affected in the inner shear layer. The curvature of the bottom wall affected the position of the zero shear stress, and it shifted towards the bottom wall than the plane wall jet. The curvature of the bottom wall enhanced the mixing, turbulence intensity and stresses in outer shear layer. Further, Okamoto and Gibson [77] did the sequel of the work of Dakos et al. [94]. Okamoto and Gibson [77] changed the convex wall from Dakos et al.'s [94] experiment to concave surface, and compared the results with flat and convex surfaces. The growth rate of the concave surface was observed about 80% than the flat surface and half of the convex surface. The turbulent heat flux and Reynolds stresses got enhanced for the concave surface than the flat surface but got reduced than the convex surface. The point of zero shear stress shifted towards the y_{max} for the concave wall surface than the convex and flat surfaces. Belilovsky [97] studied the fluid flow and thermal characteristics of a weakly heated wall jet. They assigned isothermal and adiabatic boundary conditions to the flat bottom wall surface at a Reynolds number of 55000. The author did not consider any side or back wall. By changing the incidence angle of the jet, it was noted that as the incidence angle increases, the decay rate of the axial velocity, centerline jet temperature as well as jet width increase while jet thickness decreases. Belilovsky [97] noted that the temperature potential core decayed 30% faster than the velocity potential core. A three-dimensional heated turbulent wall jet have been studied by Brindon et al. [98] through experimental method. Authors have used a flat wall surface at the jet exit Reynolds number 60,000. The test section contained a backwall at the jet exit plane, whereas no sidewall was present. The jet exit temperature was heated to $(t_{jet} - t_o)$ 25^0C. The surface temperature was measured with the infra-red thermal imaging camera whereas temperature inside the flow domain was measured with the thermocouple. The velocity field was measured with the Pitot probe tube. They found that the temperature distribution in span-wise direction across the jet is similar to the wall normal distribution exhibited by the velocity field. The decay of maximum temperature was analogous to the velocity field. Holland and Liburdy [19] compared the heated jet characteristics for a wall jet and an offset jet at a Reynolds number of 15,000. An adiabatic thermal boundary condition was considered in both the jets. Their study was limited to the two dimensional case only. Authors have reported the heat transfer characteristics at three different jet exit temperatures $(t_{jet} - t_o)$ 43^0C, 64^0C, and 86^0C above the ambient, and found that the non-dimensional temperature field is independent of the jet exit temperatures. They investigated the decay of maximum temperature, surface temperature distribution and the temperature variation in the different regions of the offset jet. They concluded that the thermal energy content within the recirculation region remains constant for the low and high offset ratios. The decay of the bottom wall temperature decreased for the offset ratio 3 but the decay increased for the offset ratio 11, as compared to the wall jet conditions.

Some of the literature which are not related to the wall jet configuration are reviewed for different heat transfer characteristics. Kim et al. [100] did the experimental investigation on the two-dimensional wall attaching offset jet for the fluid flow and heat transfer characteristics at the Reynolds numbers 6,500-39,000. Authors have varied the jet offset ratio from 0-20. They observed that the locations of minimum and maximum Nusselt numbers shift proportionally in the downstream direction with increase in the offset ratio. Assoudi et al. [101, 102] studied the effect of different densities on the offset jet through LDV method. They found that the centerline velocity decay increases and the reattachment length decreases with increase in the jet density. The numerical analysis of the heat transfer characteristics for two-dimensional turbulent jet has been studied by Vishnuvardhanarao and Das [103], Rathore and Das [46], and Kumar [26]. Kumar [26] did the numerical analysis for the heat transfer characteristics of the dual jet (wall and offset jet) with two different boundary conditions (Isothermal and heated wall jet). The author applied high Reynolds number $k-\epsilon$ turbulence model and noted that the presence of wall jet in addition to the offset jet has significant effect on the flow and turbulence characteristics. The effect of initial condition on vertical wall jets has been studied by Mokni et al. [104]. Singh et al. [27] investigated the heat transfer characteristics of a sinusoidal wavy surface.

2.1.2.2 Literature related to mean and turbulent flow characteristics

In the last few decades, the effect of geometrical boundary conditions on the fluid flow characteristics of different wall and jet configurations have been studied through experimental and numerical methods. A brief summary of the different geometrical boundary conditions on the different wall and jet configurations is provided in table 2.3. In the previous literature, the geometrical boundary conditions of the flow domain are varied by changing the shape of the bottom wall (convex, concave, sinusoidal wavy or surface roughness) or employing the backwall near the jet exit plane or sidewall parallel to the vertical jet centerline plane (symmetry plane). The fluid flow and turbulence characteristics of the jet are strongly dependent on the type of boundary conditions. So, it becomes very important to study the effect of different boundary conditions on the fluid flow and turbulence characteristics.

In this section, the turbulent wall jets with different geometrical boundary conditions are reviewed for different fluid flow and turbulent flow characteristics. The decay of mean velocity, spread of the jet stream and the turbulence characteristics of the jet are reviewed for first plane/two-dimensional wall jet followed by three-dimensional wall jet for different geometrical boundary conditions.

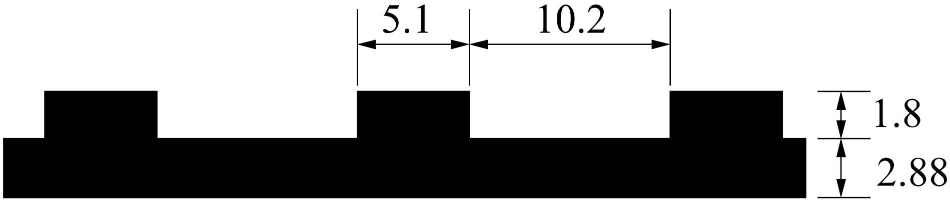
The researchers have studied the fluid flow and turbulent characteristics of the plane wall jet by changing the shape, inclination and different steps of the bottom wall. Rajarat-

Authors	BTW	BW	SW	Re	x/h	Spread Rate Lateral	Spread Rate wall-normal	Decay Rate
Sforza and Herbst [105]	flat	No	No	$109,00,000$	$0-40$	-	$(x/h)^{0.78\pm0.07}$	1.1
Koso and Ohashi [7]	flat	No	No	$66,200$	$0-50$	-	-	1.27 ± 0.02
Wu and Rajaratnam [8]	rough	No	No	$5,160-8,110$	$0-60$	0.045±0.002	-	1
Padmanabham and Gowda [2]	flat	No	No	$95,400$	$0-100$	$0.045-0.04$	$0.216-0.250$	1.15
Abrahamsson et al. [12]	flat	No	No	$5,300-1,05,000$	$50-90$	0.065	0.32	1.29
Maslov et al. [58]	rough	No	No	$25000-125000$	$50-350$ $150-350$	0.056 0.057	0.30 0.31	-
Sun and Ewing [4]	flat	Yes	No	$108,000$	$35-90$	0.053	0.27	1.14
Law and Herlina [31]	flat	No	No	$5,500-13,700$	$0-50$	0.042	0.21	1.07
Inoue et al. [10]	flat	Yes	No	100,000	$0-150$	0.0548	0.245	1.29
Hall and Ewing [9]	flat	No	No	$89,600$	$0-60$	0.051	0.28	1.144
Agelin-Chaab and Tachie [11]	flat	Yes	Yes	$5,000-20,000$	$0-120$	0.055 ± 0.001	0.250 ± 0.005	1.15
Mahmoudi et al. [106]	flat	Yes	Yes	$1,000-10,000$	$15-75$	-	0.04	1.08
Kwakye et al. [13]	flat	Yes	Yes	$12,000$	$0-60$	0.116	0.066	0.996
Poole and Hall [30]	flat	No	Yes	159,000	0-40	0.064	0.165	-
Namgyal and Hall [23]	flat	No	No	$250,000$	$0-40$	0.041	0.26	-

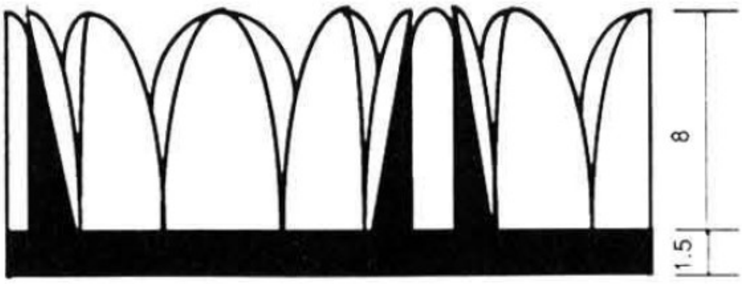
Table 2.3: Summarized literature details with different boundary conditions, BTW=bottom wall, BW=backwall, SW=sidewall,

nam [107] studied the effect of sidewalls on a plane turbulent wall jet. The sidewall enclosure having the 12.25 $inches$ width, 36 $inches$ depth and 16 $feet$ long is considered with the rectangular nozzle having aspect ratio 10.2 and 9.2. The velocity distribution near the sidewall exhibited similar characteristics as that of the plane turbulent wall jet. The author also noticed the climbing nature of the flow on the sidewalls. Rodman et al. [108] studied the two-dimensional wall jet at a Reynolds number of 9,000. The authors have studied the effect of concave curvature on the mean flow and turbulence characteristics of the shear stress profiles. The concave surface was given two different curvatures as $h/R = 0.0031$ and $h/R = 0.029$. The spread rate in the normal direction increased with the increase in curvature. The decay of maximum mean velocity got enhanced with increase in the curvature effect. The Reynolds shear stress $< u'v' >$ of the plane ($h/R = 0$) and curved ($h/R = 0.0031$) surfaces showed approximately similar behaviour upto $x/h < 100$, but after this location, the Reynolds shear stress in curve wall jet gradually increased and at $x/h = 180$, a 21% enhancement was seen. Further, Robert [109] studied the two-dimensional curved wall jet inside the quiescent medium. The effect of curvature was studied on the Reynolds shear stress and the skin friction coefficient. Fujisawa and Kobayashi [76] studied the turbulent wall jet for the fluid flow characteristics. The shape of the bottom wall was changed to a convex shape. The authors examined the turbulence characteristics by changing the radius of the convex surface from 83mm to 250mm. Matsson [110] used the concave curved wall jet. The radius of the concave curved wall was 400mm and jet height was 5mm. Further, the effect of wall inclination was investigated by Nasr and Lai [111], Hnaien et al. [112], and Pramanik and Das [113, 114] for the two-dimensional turbulent jets through numerical simulations. In some of the studies, the flat bottom wall is changed by a wavy wall. The effect of wavy wall was studied by Singh et al. [27, 85, 115, 116], Shivankar et al. [86] and Kumari and Kumar [87] for the fluid flow and turbulence characteristics. They have applied different RANS turbulence models to study the fluid flow and turbulence characteristics. The wavy surface increased the mixing up-to a certain amplitude of the surface waviness.

The three-dimensional wall jet was studied by changing the backwall condition, bottom wall roughness and step wall. Sforza and Herbst [105] investigated the 3D-rectangular wall jet over a flat plate at a Reynolds number of 52,760. The authors did not have any back or sidewall adjacent to the jet stream. The velocity field was measured with the constant current hot-wire anemometer. The velocity flow-field was divided into three different regions similar to Launder and Rodi [50]. After the potential core region, the mean velocity decay in transition and self-similar regions occurred as per the power law. The velocity decayed approximately 10% faster in wall jet than the free jet in self-similar region. The



(a)



(b)

Figure 2.9: Bottom wall-surface roughness (a) Strip roughness and (b) Flower shaped roughness (all dimensions are in mm), investigated by Wu and Rajaratnam [8]

authors have noted that the spread in wall-normal direction is smaller than the free jet. The lateral spread of the wall jet increased as compared to the free jet. The skin friction coefficient in three-dimensional turbulent wall jet was calculated in transition and self-similar regions and compared with the two-dimensional wall jet. The decay of the skin friction coefficient in three-dimensional case was approximately 60% higher than in the two-dimensional wall jet. Rajaratnam and Pani [1] experimentally investigated the three-dimensional turbulent wall jet inside a large tank over a flat plate. The effect of the tank's wall inside the flow domain was negligible. Further, Wu and Rajaratnam [8] investigated the effect of surface roughness on the spreading and mixing behaviour of the wall jet at the Reynolds number of 5,160 and 8,110. The wall jet flow was generated inside the submersed tank ($1.1m$ wide, $1.22m$ deep and $3m$ long), where the surface roughness of the bottom wall was changed using the strip and flower shape as shown in Figure 2.9. The surface roughness significantly changed the boundary shear stresses. The boundary shear stress varied inversely with x^2 in the central plane. The skin friction coefficient increased linearly with the relative roughness of the bottom wall. Maslov et al. [58] compared the rough and smooth flat surfaces ($95cm \times 42cm$) of a three-dimensional turbulent wall jet for the Reynolds numbers 25,000-125,000. The dimension of the surface roughness was $2mm$, approximately. The authors measured the normal and lateral plane velocity distribution at the downstream location $x/d = 100$. The roughness of the wall surface de-

wall condition	size of backwall	lateral spread angle	wall-normal spread angle
No wall	-	51^0	5.85^0
low wall	$46d \times 240d$	47^0	5.16^0
High wall	$92d \times 240d$	52^0	4.89^0

Table 2.4: Effect of back wall on spreading rate, reported by Eriksson et al. [24]

creased the maximum mean velocity about 20%, whereas boundary layer thickness increased about 2.5 times than the smooth wall surface. Namgyal and Hall [23] studied the three-dimensional wall jet over a flat plate ($2.49m \times 2.08m$) at a Reynolds number of 250,000. Namgyal and Hall [23] also did not consider any back or sidewall adjacent to the jet flow for circular nozzle. The spread in lateral direction was approximately 5.5 times more than in the wall-normal directions. The variation of the mass entrainment inside the three-dimensional wall jet was also compared with the free jet. It is noted that the mass entrainment becomes nearly half of the free jet in the three-dimensional wall jet. The all six components of the Reynolds shear stress were measured by the authors. In the wall normal direction, the shear stress component $< u'v' >$ dominated while in the lateral direction $< u'w' >$dominated. Koso and Ohhashi [7, 117], Godi et al. [28], Padmanabham and Gowda [2, 3] considered the three-dimensional wall jet over a flat plate. Abrahamsson et al. [12] also investigated the three-dimensional wall jet over a flat plate for the Reynolds number 5,300-1,05,000. They have found the growth rate 4.9 times higher in lateral direction than in the wall normal direction.

Further, some literature is found in which the flow field was characterized by using the backwall at the jet exit plane. Eriksson et al. [24] studied the influence of the back wall at the Reynolds number of 10,000. The near field of the spreads in wall-normal and lateral directions are influenced by the backwall conditions. The spread angle for backwall condition are listed in table 2.4. The wall-normal spread was more for the no backwall case than the case with the backwall. The authors have also noticed the smaller spread in the lateral direction when there was smaller backwall. In the far-field locations, the spread ratio (lateral to normal) was 4.9 similar to the value obtained by Abrahamsson et al. [12]. Sun and Ewing [4] also studied the effect of backwall for the round wall jet at the Reynolds number of 65,000 and 108,000. The jet spread rate was not affected by the presence of backwall after $x/d \geq 10$. The wall jet without backwall spreads more quickly as compared to with the backwall conditions. Inoue et al. [10] used backwall having the dimension of $40d \times 90d$ for the three-dimensional wall jet at a Reynolds number of 10,000. The spread and decay rate for the backwall condition are provided in table 2.3. Inoue et al. [10] compared the three-dimensional jet with back wall condition with the plane wall jet. Further, Hall and

Ewing [9] also used a $1.2m$ high and $2.4m$ wide back wall at the jet exit plane to prevent the entrainment from behind the jet for three dimensional wall jet, but they did not compare the effect of backwall condition with the no backwall condition. Law and Herlina [31], Herlina and Law [118] , Agelin-Chaab and Tachie [11, 119], Assoudi et al. [68, 101], Mahmoudi et al. [106] and Kwakye et al. [13] studied the three-dimensional wall jet inside the different widths of the sidewall enclosure. Law and Herlina [31] and Herlina and Law [118] considered the $181d$ of sidewall enclosure. It must be noted here that sidewalls are placed quite far from the vertical jet centerline. Therefore, effect of sidewalls on the flow field was not discussed. Herlina and Law [118] studied the mixing characteristics of a circular wall jet through the combined particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) methods. The authors used the jet exit diameter $5.5mm$, and the Reynolds number as $5,500$, $12,200$, and $13,700$. They measured the mean flow and turbulence characteristics up-to a downstream location of 50 nozzle diameter and reported that the wall jet was still developing within that length and did not achieve self similarity. Further, Law and Herlina [31] studied the kinematic and scalar mixing of the circular wall jet for the similar condition used by Herlina and Law [118]. Authors noted that the velocity spreading data is consistent with the data of Rajaratnam and Pani [1], but the concentration spreading rate is 1.5 times higher. The ratio of the concentration spreading (wall normal to lateral) was noted approximately 5. Agelin-Chaab and Tachie [11, 119] studied the wall jet and offset jet at the Reynolds number of 5,000, 10,000 and 20,000. Further, Agelin-Chaab and Tachie [11, 120] investigated the fluid flow characteristics of a three dimensional turbulent wall jet and offset jet by using SWE with a width of $71d$ at the Reynolds numbers 5,000, 10,000 and 20,000. They studied the mean flow and turbulent characteristics over a larger downstream distance and found that the decay and spread rates were independent of the Reynolds number and small offset distance. Agelin-Chaab and Tachie studied the effect of Reynolds number on a three dimensional wall jet [11] and offset jet [119]. Reynolds number was varied as 5000, 10,000 and 20,000. The authors placed the sidewall along the vertical jet centerline plane but did not consider its effect on the flow-field because it was placed at a very large distance from the jet. Agelin-Chaab and Tachie [11, 119] studied the different configurations of wall and nozzle through PIV technique. Agelin-Chaab and Tachie [11, 119] studied the different combinations of wall jet at the Reynolds numbers of 10,000, 20,000 and 30,000 inside a $1000mm \times 500mm \times 300mm$ side wall enclosure. Authors did not consider any effect of sidewall on the fluid flow characteristics. They considered the fully developed jet exit profile obtained by a $1000mm$ long round pipe. They found that the early region of the jet is strongly dependent on the offset ratio (defined as the ratio of the offset distance of the nozzle from the bottom wall to the nozzle diameter) and the Reynolds number. Zhang et al. [121] did the large eddy simulation for a circular wall jet to analyse the mixing characteristics and compared different turbulence models. Authors considered the sidewall at the lateral positions, but it was located vary far (location of sidewall from the centerline plane / nozzle diameter ≈ 54) from the flow field. Assoudi et al. [68, 101] studied the dynamic and thermal characteristics of the turbulent wall and offset jets. They compared the different jet and wall combinations and found that the near field of the jet is influenced by the initial condition whereas the far field characteristics become independent of the initial condition of the jet. They also investigated the effect of density on the offset jet through LDV method. They found that centerline velocity decay increased and the reattachment length decreased with increase in the jet density. Some of the authors also studied the three dimensional wall jet for the curved surface. Gowda and Durbha [122] studied the effect of convex wall on the development of the three-dimensional wall jet. The three different curvatures of the convex wall as $R = 3500mm$, $1500mm$ and $350mm$ were considered. The decay of maximum streamwise velocity increased by introducing the curvature on the wall. The decay rate became approximately twice in 350mm radius of convex curvature than the plane wall surface. The wall-normal spread increased with decrease in the radius of convex surface, whereas lateral spread decreased with decrease in the radius of convex surface. The lateral spread decreased approximately 16% in convex surface having radius $350mm$ as compared to the plane surface. The point of zero shear stress moved closer to the wall with increase in the curvature parameters. The generation of turbulent kinetic energy enhanced by nearly 2.5 times in convex surface having radius $350mm$ as compared to the plane surface. Further, Kim et al. [123] also studied the three-dimensional wall jet over a curved surface. The flow development of the wall jet was strongly influenced by the curvature. Kim et al. [123] investigated the fluid flow characteristics for the Reynolds number 3,300, 7,100, and 11,800 at four different nozzle angles (0^0, 15^0, 30^0, and 45^0). The spread in wall-normal direction was higher for lower Reynolds number over the curved surfaces for all the nozzle inclination angle.

2.1.3 Summary of the literature

In this chapter, the literature related to different initial and boundary conditions for different turbulent jet configurations are reviewed. It is evident from the literature, despite of the different studies of the initial and boundary conditions of the turbulent jets, that the effect of initial and boundary conditions on three-dimensional turbulent wall jet has not been studied in detail. For example, inconsistency in mean and turbulent flow characteristics of the three-dimensional wall jet is present at different initial conditions. The free jet, wall jet and offset jet develop differently in the downstream directions due to anisotropic behaviour of the wall. Whenever any solid wall interacts with the flow stream of the jet, it changes the flow characteristics like spreading, decaying, mixing etc. In the real practice, the wall jet is seen with developing initial velocity profile inside a sidewall enclosure. The developing velocity profile of the wall jet in sidewall enclosure exhibits different characteristics of the flow development. This needs to be addressed thoroughly through experimental and numerical methods.

In the open literature, there are plethora of work on the effect of initial condition on free jet and two-dimensional wall jet. These studies are carried out either by the contoured nozzle or a long pipe. The three-dimensional wall jet for different developing initial velocity profile is missing entirely. Although, the effect of boundary conditions on passive quantities of the turbulent jet is studied, but the heated three-dimensional wall jet got very less attention. The effect of back wall [4, 24], corner wall jet [30], different bottom wall geometries [77, 94, 122] is studied but the effect of sidewall on the three-dimensional wall jet is not characterized thoroughly through either experimental or numerical methods. Law and Herlina [31], Herlina and Law [118], Agelin-Chaab and Tachie [11, 119] and Mahmoudi et al. [106] studied the three-dimensional turbulent wall jet inside the sidewall enclosure, but the authors did not consider the effect of sidewall boundary conditions. These studies considered the different widths of the sidewall enclosure and reported the mean and turbulent flow characteristics at different jet exit Reynolds numbers through experimental methods. But, in actual practice, the sidewalls are always present like internal cooling of turbine blade, solar air heater, vegetable dryer. These equipment have developing jet exit velocity profile inside the sidewall enclosure. Based on this, the motivation of the present study is derived.

The goal of the present study is to understand the effect of different developing velocity profiles inside the sidewall enclosure through experimental and numerical methods. The mean flow and heat transfer characteristics are obtained through experimental methods while the numerical study provides the turbulent characteristics. The mean velocity is measured with a single probe hotwire anemometer while temperature is measured through a fine wire K-type of thermocouple. The surface temperature is measured with the infrared thermal imaging camera. The velocity and temperature data are presented at different downstream locations in the form of the line profile and contour plots for mean flow characteristics. The mean flow characteristics are validated with the different low Reynolds number turbulence models (Yang and Shih [47] and Launder and Sharma [48]).